

# Black Hole Spectral States and Physical Connections

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## Abstract

The dramatic changes seen in the X-ray spectral and timing properties of accreting black hole candidates (BHCs) provide important clues about the accretion and jet formation processes that occur in these systems. Dividing the different source behaviors into spectral states provides a framework for studying BHCs. To date, there have been three main classification schemes with Luminosity-based, Component-based, or Transition-based criteria. The canonical, Luminosity-based criteria and physical models that are based on this concept do not provide clear explanations for several phenomena, including hysteresis of spectral states and the presence of jets. I discuss the re-definitions of states, focusing on an application of the Component-based states to more than 400 *RXTE* observations of the recurrent BHC 4U 1630–47. We compare the X-ray properties for the recent 2002–2004 outburst to those of an earlier (1998) outburst, during which radio jets were observed. The results suggest a connection between hysteresis of states and major jet ejections, and it is possible that both of these are related to the evolution of the inner radius of the optically thick accretion disk.

*Key words:* Black hole physics, Accretion disks, Black hole jets, Outflows, X-ray transients

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## 1 Introduction

It has long been known that accreting black hole candidates (BHCs) exhibit a wide array of emission properties, and, over the years, these properties have been divided in various ways into spectral states. The first state transition was detected in the early 1970s using *Uhuru* when the 2–6 keV flux from Cyg X-1 was seen to decrease by a factor of four while the 10–20 keV flux increased by a factor of two. Upon the discovery of this change, Tananbaum et al. (1972) called this a transition from a “low” state to a “high” state based on the change

in the 2–6 keV flux. It was also realized at this time that the radio properties can be associated with the X-ray states as Hjellming and Wade (1971) also reported a radio detection from Cyg X-1 that Tananbaum et al. (1972) associated with the low state. Since these early discoveries, more sensitive, higher-throughput, broadband X-ray detectors and multi-wavelength coverage have provided a much more detailed understanding of the phenomenology of spectral states, including both the spectral (e.g., Wilson and Rothschild, 1983; Mitsuda et al., 1984; Tanaka and Shibazaki, 1996; Grove et al., 1998) and timing (e.g., Miyamoto et al., 1991; van der Klis, 2004) properties. Also, theoretical work has provided insights into the physical processes that are occurring in these binary accreting BHC systems (e.g., Shakura and Sunyaev, 1973; Abramowicz et al., 1988; Esin et al., 1997).

Some of the best examples of broadband, 1–2000 keV, energy spectra combine spectra from the *Compton Gamma-Ray Observatory's (CGRO)* OSSE instrument with spectra from various soft X-ray instruments (Grove et al., 1998). From these, it is clear that there are three components that dominate BHC spectra: The soft component; the cutoff power-law component; and the steep power-law component. The soft component is due to thermal emission from an optically thick accretion disk. In many cases, the shape of this component is consistent with the predictions for a Shakura and Sunyaev (1973) disk with an inner disk temperature of  $\sim 1$  keV. Historically, the cutoff power-law component has been explained by invoking inverse Comptonization from a hot electron “corona” with a thermal energy distribution at a temperature of  $\sim 100$  keV. However, the geometry of the corona is not known, and the question of whether jets may be involved in X-ray production is a current topic of debate (Markoff and Nowak, 2004). The origin of the steep power-law component is also a topic of debate (see, e.g., McClintock and Remillard, 2003). Although the emission mechanism may be inverse Comptonization, the fact that the component extends to MeV energies or beyond without a cutoff (Tomsick et al., 1999) makes it unlikely that it comes from a thermal electron distribution. Hybrid thermal/non-thermal models have been developed (Coppi, 1992), but the mechanism for accelerating the electrons is still unclear.

When the thermal component is present, it is usually accompanied by the steep power-law component at some level, and if the thermal component dominates the 2–10 keV band, it is traditionally said that the source is in the “High-Soft” state. At other times, when the cutoff power-law component dominates the entire X-ray spectrum, this state has come to be known as the “Low-Hard” state. The high throughput X-ray instruments such as *Ginga* and the *Rossi X-ray Timing Explorer (RXTE)* have made it clear that the X-ray timing properties are closely related to the spectral properties, and they are also important in defining the spectral states. While strong timing noise is seen in the High-Soft state and weak noise is seen in the Low-Hard state, it was noticed by Miyamoto et al. (1991) and others that at very high luminosities, the

power spectra typically show intermediate levels of timing noise and usually exhibit quasi-periodic oscillations (QPOs). This state became known as the Very High State (VHS). In addition to the VHS, the presence of another distinct state, the “Intermediate” state (IS), with properties (luminosity, timing noise, spectral hardness) intermediate to the Low-Hard and High-Soft states was suggested (Belloni et al., 1996; Mendez and van der Klis, 1997). When the very low luminosity “Off” or “Quiescent” state is included, there are five canonical spectral states: VHS, High-Soft, IS, Low-Hard, and Quiescent.

Based on this Luminosity-based classification of states, a physical picture including advection-dominated accretion flows (ADAFs) was advanced to explain many of the X-ray properties (Esin et al., 1997). This picture supposes that all of the emission properties are set by changes in the mass accretion rate ( $\dot{M}$ ). While other physical parameters, such as the inner radius of the optically thick disk and the size of the corona might change, the concept of the model is these are tied to  $\dot{M}$ . While relatively successful in describing some of the spectral properties of BHCs, this model clearly misses some of the important BHC physics. In the following, I describe some of the evidence for other physics. Then, I discuss state classifications that have been recently advanced in an attempt to adapt the spectral state definitions in light of recent observational results. Finally, I use a large set of *RXTE* observations of the BHC transient 4U 1630–47 as a case study and discuss the results.

## 2 Beyond the Canonical Spectral States

### 2.1 Radio Connections to States

Although it has been known for some time that many of the BHC systems are radio emitters, most of the systematic studies of how the radio properties are connected to the spectral states have only been carried out over the past several years. It has now been well-established that steady, flat-spectrum radio emission is associated with the Low-Hard state (Corbel et al., 2000; Fender, 2001). For two sources, this radio emission is resolved, indicating that radio jets are present (Stirling et al., 2001; Dhawan et al., 2000). In many cases, the radio and X-ray fluxes are strongly correlated (Gallo et al., 2003), indicating that the radio and X-ray emission mechanisms are closely linked. The presence of a steady jet in the Low-Hard state has implications for the Esin et al. (1997) physical model as this state is where the ADAF forms when accretion energy is advected into the black hole. It has been suggested that this accretion energy may be lost to the jet instead (Blandford and Begelman, 1999; Fender et al., 2003).

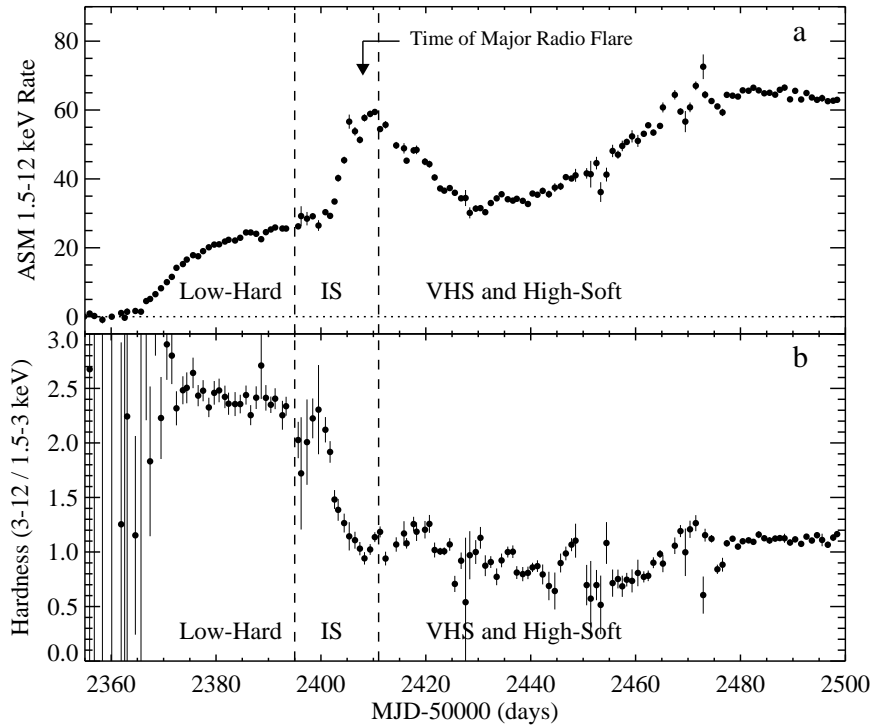


Fig. 1. Demonstration of X-ray and radio evolution that has been seen for several BHCs. The light curve (a) and hardness ratio values (b) are for the BHC GX 339–4. The figure has been adapted from Corbel et al. (2004), and the time of the major radio ejection (marked with an arrow) comes from Gallo et al. (2004). For several systems, it has been found that major radio ejections follow a bright “Low-Hard” state and occur close to a state transition.

In addition to the steady radio jets, BHC systems show major, discrete jet ejections when the systems are at high X-ray fluxes (likely at high  $\dot{M}$ ). Although these major jet ejections were initially given more attention than the steady jets likely due to apparently superluminal motions measured for some of the discrete ejections (Mirabel and Rodríguez, 1999), a clear connection between the ejections and specific spectral states has been lacking. With studies of several recent BHC outbursts where major ejections occurred, this connection may be becoming clearer. The example in Figure 1 shows the evolution for the BHC GX 339–4 where the source started off in the Low-Hard state, made a transition to the IS, and then a major radio flare occurred when the source made a transition to the VHS, and similar evolution has been seen for several other sources (Corbel et al., 2004; Fender et al., 2004).

## 2.2 Hysteresis and Possible Second Physical Parameters

BHC transients show hysteresis in the evolution of their spectral states during their rise and decay (see van der Klis, 2004, and references therein). Several examples of hysteresis and luminosity-independence of states are given in Tomsick (2004). The most common form of hysteresis is that the “Low-Hard” state sometimes occurs at the peak X-ray luminosity for a given BHC outburst. This hysteresis is not explained by physical models of BHCs such as the Esin et al. (1997) model described above, but it very likely indicates that there is at least one physical parameter that is at least partially independent of  $\dot{M}$  that is important for setting the spectral state (Homan et al., 2001; Tomsick, 2004). Several second parameters are worth considering, including the presence and power of an outflow or jet, the fraction of accretion energy dissipated in the corona (vs. the optically thick portion of the disk), the accretion rate in the corona vs. the accretion rate in the disk (in two flow models such as Chakrabarti and Titarchuk, 1995), and the inner radius of the optically thick disk ( $R_{\text{in}}$ ), even though one might expect  $R_{\text{in}}$  to be at least partially dependent on  $\dot{M}$ .

## 3 Re-Definitions of States

In light of our changing view of spectral states and the physics behind accreting BHCs, two re-definitions of BHC states have been advanced. One of these re-definitions by McClintock and Remillard (2003) is based on the details of the X-ray spectral and timing parameters and relies most heavily on the strength of the three spectral components described above. Generally, sources are in the “Thermal-Dominant” (TD) state when the soft component dominates; the “Steep Power-Law” (SPL) state when the spectra have a strong power-law component with a photon index ( $\Gamma$ ) steeper than 2.4; and the “Hard” state when the spectra are dominated by a cutoff power-law component with  $1.5 < \Gamma < 2.1$  and the level of timing noise is high. An important feature of the McClintock and Remillard (2003) classification scheme is that the authors have determined quantitative state definitions using 30 *RXTE* spectra from 15 different BHC sources. This gives precise meaning to the states and allows for clearer source-to-source comparisons.

Another re-definition scheme (Homan and Belloni, 2004; Belloni, 2005) groups the states by location in the hardness-intensity diagram according to where sharp changes in emission properties occur. The following contains some discussion of this scheme, but we refer to the paper in these proceedings by T. Belloni for details. In summary, three main classification schemes have been advanced: The canonical definitions are *Luminosity-based*; the McClintock and Remillard

(2003) definitions are *Component-based*; and the Homan and Belloni (2004) definitions are *Transition-based*.

#### 4 Application to 4U 1630–47

The recurrent BHC transient 4U 1630–47 recently finished one of its brightest and longest outbursts at the end of 2004. It is one of the most active BHC transients with 17 detected outbursts going back to 1969. The possibility to compare different outbursts makes it an interesting source to study, and we have analyzed data from over 400 *RXTE* observations taken during its 1998 outburst (Tomsick and Kaaret, 2000; Dieters et al., 2000; Trudolyubov et al., 2001) and its recent outburst (Tomsick et al., 2005). This provides an especially interesting comparison because strong and highly polarized radio emission was detected during the 1998 outburst (likely indicating the presence of radio jets) but not during its 2002–2004 outburst (Hjellming et al., 1999; Hannikainen et al., 2002; Tomsick et al., 2005).

As described in detail in Tomsick et al. (2005), we applied the quantitative McClintock and Remillard (2003) state definitions to 4U 1630–47 *RXTE* data. The results of our comparison between the 2002–2004 and 1998 outbursts are shown in Figure 2. The 1998 outburst follows a pattern that is now recognized as being rather typical for BHCs (see Figure 1). The source begins the outburst by reaching a relatively bright Hard state before making a transition to an intermediate state and then to a SPL state. Radio emission likely signals a major jet ejection starting around the time that the source makes a transition to the SPL state. The motion in the hardness-intensity diagram is counter-clockwise, which is similar to the outbursts that have been used as the basis for the Transition-based state definitions (Homan and Belloni, 2004). The hysteresis in the Hard state transition levels is clear with the transition from the Hard state at the beginning of the outburst being a factor of five or more higher in flux than the transition to the Hard state at the end of the outburst.

The behavior during the 2002–2004 outburst is in sharp contrast to the 1998 outburst. The rise of the outburst is very fast, and there is no evidence that the source ever entered a bright Hard state. The overall outburst is considerably softer, with the source entering the TD state on several occasions. Radio observations yielded non-detections for the TD, IS, and SPL states. The hardness-intensity diagram shows an evolution that is completely different from 1998, with the source being in the TD state during its rise. The differences between outbursts indicates a connection between the X-ray behaviors and radio jets. This connection may be related to the hardness of the outburst or to more subtle X-ray features such as the source entering a bright

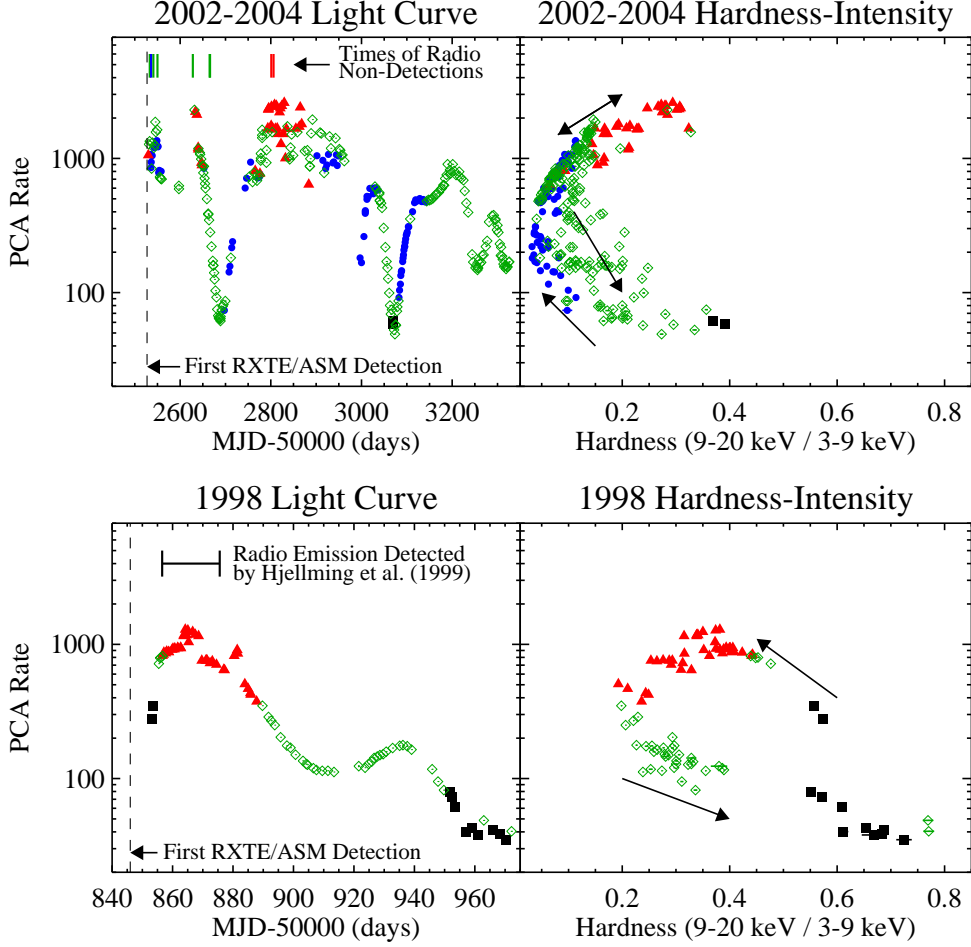


Fig. 2. Properties of the 4U 1630–47 outbursts in 2002–2004 (top two panels) and 1998 (bottom two panels). The data are from pointed *RXTE* observations (see Tomsick et al., 2005, for details). The colors/symbols correspond to the Component-based McClintock and Remillard (2003) states as follows: Red triangles = Steep Power-Law; Green open diamonds = Intermediate State; Blue circles = Thermal-Dominant; Black squares = Hard state. For each outburst, 3–20 keV PCA light curves are shown along with an indication of the results of radio observations, and hardness-intensity diagrams are shown, with arrows indicating the temporal evolution of the source in the diagram.

Hard state or counter-clockwise motion in the hardness-intensity diagram.

## 5 Connections between Hysteresis, Jets, and $R_{\text{in}}$

It is clear that physical processes are operating in BHC systems that are not captured by canonical state definitions and the standard physical picture that changes in emission properties are driven only by changes in mass accretion rate. Observations of hysteresis of state transitions and radio jets are examples

of phenomena that do not have good physical explanations. Observations of 4U 1630–47 as well as other BHC systems suggest that the two phenomena may be related. For GX 339–4, XTE J1859+226, XTE J1550–564, and 4U 1630–47 in 1998, major radio ejections are preceded by bright Hard states, while the recent outburst from 4U 1630–47 showed no bright Hard state (i.e., hysteresis) and no major radio ejection.

Additionally, recent theoretical work suggests that both phenomena (hysteresis and major radio ejections) may be regulated by the location of the inner radius of the optically thick accretion disk,  $R_{\text{in}}$ . Meyer-Hofmeister et al. (2005) suggest that if  $R_{\text{in}}$  becomes very large when sources enter quiescence, allowing for a central corona with strong hard X-ray emission, then this hard X-ray emission may inhibit the formation of the inner optically thick disk. If this occurs, then the hard X-ray source (and thus the Hard state) may survive up to very high accretion rates. The “unified model” for BHC jets by Fender et al. (2004) has been inspired, in part, by the Transition-based state definitions. In this model, the main physical parameter that determines the nature of the outflow is also  $R_{\text{in}}$ . The slow, steady compact jets are produced when  $R_{\text{in}}$  is large, while the disk must approach the black hole (small  $R_{\text{in}}$ ) before the highly relativistic major outflows can be produced. Although more work is required to show that  $R_{\text{in}}$  is indeed the other important physical parameter in setting the BHC emission properties, understanding the accretion geometries and how they are related to the different kinds of jets would be a major step forward in our understanding of the disk/jet connection.

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## References

- Abramowicz, M. A., Czerny, B., Lasota, J. P., Szuszkiewicz, E., September 1988. Slim Accretion Disks. *ApJ* 332, 646–658.
- Belloni, T., April 2005. Black Hole States: Accretion and Jet Ejection. [astro-ph/0504185](#).



- Belloni, T., Mendez, M., van der Klis, M., Hasinger, G., Lewin, W. H. G., van Paradijs, J., December 1996. An Intermediate State of Cygnus X-1. *ApJ* 472, L107.
- Blandford, R. D., Begelman, M. C., February 1999. On the Fate of Gas Accreting at a Low Rate on to a Black Hole. *MNRAS* 303, L1–L5.
- Chakrabarti, S., Titarchuk, L. G., December 1995. Spectral Properties of Accretion Disks around Galactic and Extragalactic Black Holes. *ApJ* 455, 623.
- Coppi, P. S., October 1992. Time-dependent models of magnetized pair plasmas. *MNRAS* 258, 657–683.
- Corbel, S., Fender, R. P., Tomsick, J. A., Tzioumis, A. K., Tingay, S., December 2004. On the Origin of Radio Emission in the X-Ray States of XTE J1650-500 during the 2001-2002 Outburst. *ApJ* 617, 1272–1283.
- Corbel, S., Fender, R. P., Tzioumis, A. K., Nowak, M., McIntyre, V., Durouchoux, P., Sood, R., July 2000. Coupling of the X-ray and Radio Emission in the Black Hole Candidate and Compact Jet Source GX 339-4. *A&A* 359, 251–268.
- Dhawan, V., Mirabel, I. F., Rodríguez, L. F., November 2000. AU-Scale Synchrotron Jets and Superluminal Ejecta in GRS 1915+105. *ApJ* 543, 373–385.
- Dieters, S. W., Belloni, T., Kuulkers, E., Woods, P., Cui, W., Zhang, S. N., Chen, W., van der Klis, M., van Paradijs, J., Swank, J., Lewin, W. H. G., Kouveliotou, C., July 2000. The Timing Evolution of 4U 1630-47 during Its 1998 Outburst. *ApJ* 538, 307–314.
- Esin, A. A., McClintock, J. E., Narayan, R., November 1997. Advection-dominated Accretion and the Spectral States of Black Hole X-Ray Binaries: Application to Nova Muscae 1991. *ApJ* 489, 865.
- Fender, R. P., March 2001. Powerful Jets from Black Hole X-Ray Binaries in Low/Hard X-Ray States. *MNRAS* 322, 31–42.
- Fender, R. P., Belloni, T. M., Gallo, E., October 2004. Towards a Unified Model for Black Hole X-Ray Binary Jets. *MNRAS*, 538.
- Fender, R. P., Gallo, E., Jonker, P. G., August 2003. Jet-Dominated States: An Alternative to Advection across Black Hole Event Horizons in ‘Quiescent’ X-Ray Binaries. *MNRAS* 343, L99–L103.
- Gallo, E., Corbel, S., Fender, R. P., Maccarone, T. J., Tzioumis, A. K., January 2004. A Transient Large-Scale Relativistic Radio Jet from GX 339-4. *MNRAS* 347, L52–L56.
- Gallo, E., Fender, R. P., Pooley, G. G., September 2003. A Universal Radio-X-Ray Correlation in Low/Hard State Black Hole Binaries. *MNRAS* 344, 60–72.
- Grove, J. E., Johnson, W. N., Kroeger, R. A., McNaron-Brown, K., Skibo, J. G., Philips, B. F., June 1998. Gamma-Ray Spectral States of Galactic Black Hole Candidates. *ApJ* 500, 899.
- Hannikainen, D., Sault, B., Kuulkers, E., Wu, K., Jones, P., Hunstead, R., September 2002. Follow-Up Radio Observations of the Black Hole Candidate 4U 1630-47. *The Astronomer’s Telegram* 108.
- Hjellming, R. M., Rupen, M. P., Mioduszewski, A. J., Kuulkers, E., McCol-

- lough, M., Harmon, B. A., Buxton, M., Sood, R., Tzioumis, A., Rayner, D., Dieters, S., Durouchoux, P., March 1999. Radio and X-Ray Observations of the 1998 Outburst of the Recurrent X-Ray Transient 4U 1630–47. *ApJ* 514, 383–387.
- Hjellming, R. M., Wade, C. M., August 1971. Radio Emission from X-Ray Sources. *ApJ* 168, L21.
- Homan, J., Belloni, T., December 2004. The Evolution of Black Hole States. *astro-ph/0412597*.
- Homan, J., Wijnands, R., van der Klis, M., Belloni, T., van Paradijs, J., Klein-Wolt, M., Fender, R., Méndez, M., February 2001. Correlated X-Ray Spectral and Timing Behavior of the Black Hole Candidate XTE J1550–564: A New Interpretation of Black Hole States. *ApJS* 132, 377–402.
- Markoff, S., Nowak, M. A., July 2004. Constraining X-Ray Binary Jet Models via Reflection. *ApJ* 609, 972–976.
- McClintock, J., Remillard, R., 2003. Black Hole Binaries. Review Article *astro-ph/0306213*.
- Mendez, M., van der Klis, M., April 1997. The EXOSAT Data on GX 339–4: Further Evidence for an “Intermediate” State. *ApJ* 479, 926.
- Meyer-Hofmeister, E., Liu, B. F., Meyer, F., March 2005. Hysteresis in Spectral State Transitions - A Challenge for Theoretical Modeling. *A&A* 432, 181–187.
- Mirabel, I. F., Rodríguez, L. F., 1999. Sources of Relativistic Jets in the Galaxy. *ARA&A* 37, 409–443.
- Mitsuda, K., Inoue, H., Koyama, K., Makishima, K., Matsuoka, M., Ogawara, Y., Suzuki, K., Tanaka, Y., Shibazaki, N., Hirano, T., 1984. Energy Spectra of Low-Mass Binary X-Ray Sources Observed from TENMA. *PASJ* 36, 741–759.
- Miyamoto, S., Kimura, K., Kitamoto, S., Dotani, T., Ebisawa, K., December 1991. X-Ray Variability of GX 339–4 in its Very High State. *ApJ* 383, 784–807.
- Shakura, N. I., Sunyaev, R. A., 1973. Black Holes in Binary Systems. Observational Appearance. *A&A* 24, 337–355.
- Stirling, A. M., Spencer, R. E., de la Force, C. J., Garrett, M. A., Fender, R. P., Ogle, R. N., November 2001. A Relativistic Jet from Cygnus X-1 in the Low/Hard X-Ray State. *MNRAS* 327, 1273–1278.
- Tanaka, Y., Shibazaki, N., 1996. X-Ray Novae. *ARA&A* 34, 607–644.
- Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R., Jones, C., October 1972. Observation of a Correlated X-Ray Transition in Cygnus X-1. *ApJ* 177, L5.
- Tomsick, J. A., July 2004. The Evolution of Accreting Black Holes in Outburst. In: AIP Conf. Proc. 714: X-ray Timing 2003: Rossi and Beyond, *astro-ph/0401189*. pp. 71–78.
- Tomsick, J. A., Corbel, S., Goldwurm, A., Kaaret, P., May 2005. X-Ray Observations of the Black Hole Transient 4U 1630–47 During Two Years of X-Ray Activity. *astro-ph/0505271*, Accepted by *ApJ*.

- Tomsick, J. A., Kaaret, P., July 2000. X-Ray Spectral and Timing Evolution during the Decay of the 1998 Outburst from the Recurrent X-Ray Transient 4U 1630–47. *ApJ* 537, 448–460.
- Tomsick, J. A., Kaaret, P., Kroeger, R. A., Remillard, R. A., February 1999. Broadband X-Ray Spectra of the Black Hole Candidate GRO J1655–40. *ApJ* 512, 892–900.
- Trudolyubov, S. P., Borozdin, K. N., Priedhorsky, W. C., April 2001. *RXTE* Observations of 4U 1630–47 during the peak of its 1998 outburst. *MNRAS* 322, 309–320.
- van der Klis, M., October 2004. A Review of Rapid X-Ray Variability in X-Ray Binaries. *astro-ph/0410551*.
- van der Klis, M., 1995. Rapid Aperiodic Variability in X-Ray Binaries. In: *X-ray Binaries*. Cambridge University Press. pp.252-307.
- Wilson, C. K., Rothschild, R. E., November 1983. Observations of a Hard X-Ray Component in the Spectrum of Nova Ophiuchi. *ApJ* 274, 717–722.